Microlensing Exoplanet Mass Measurement in WFIRST Era

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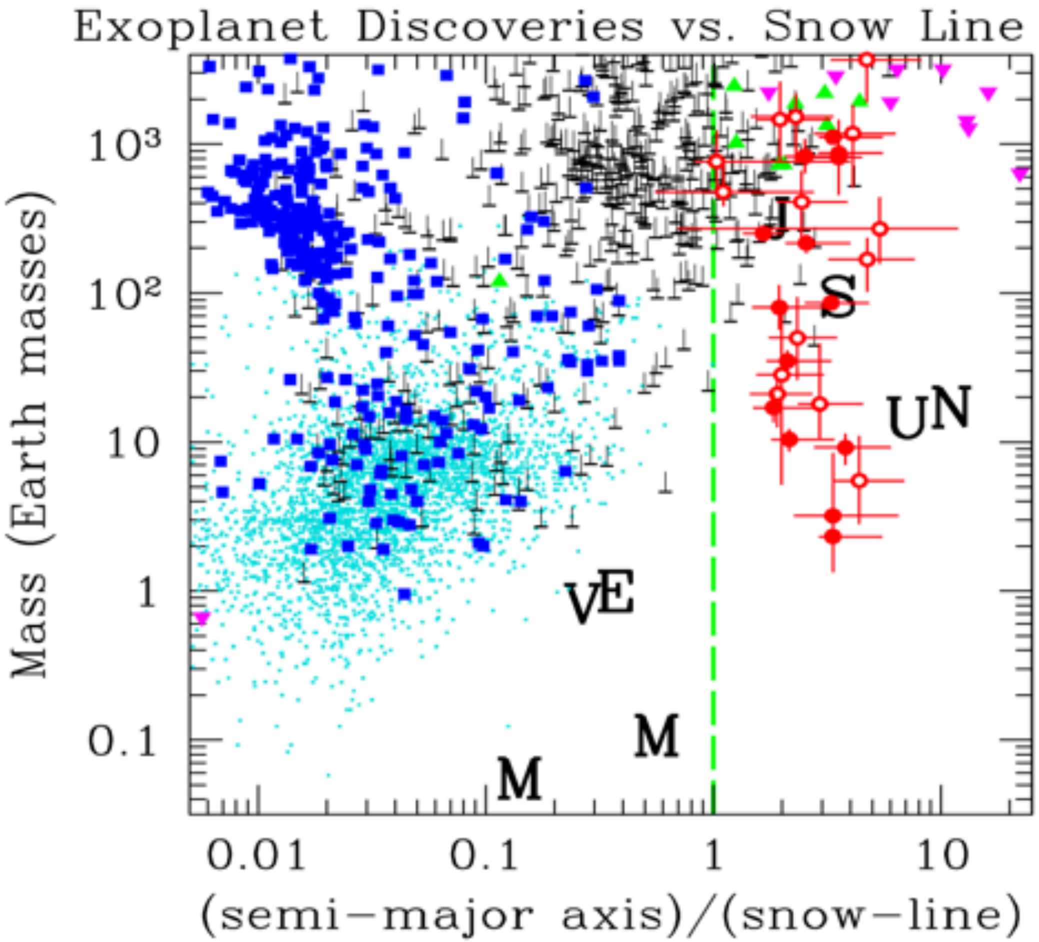
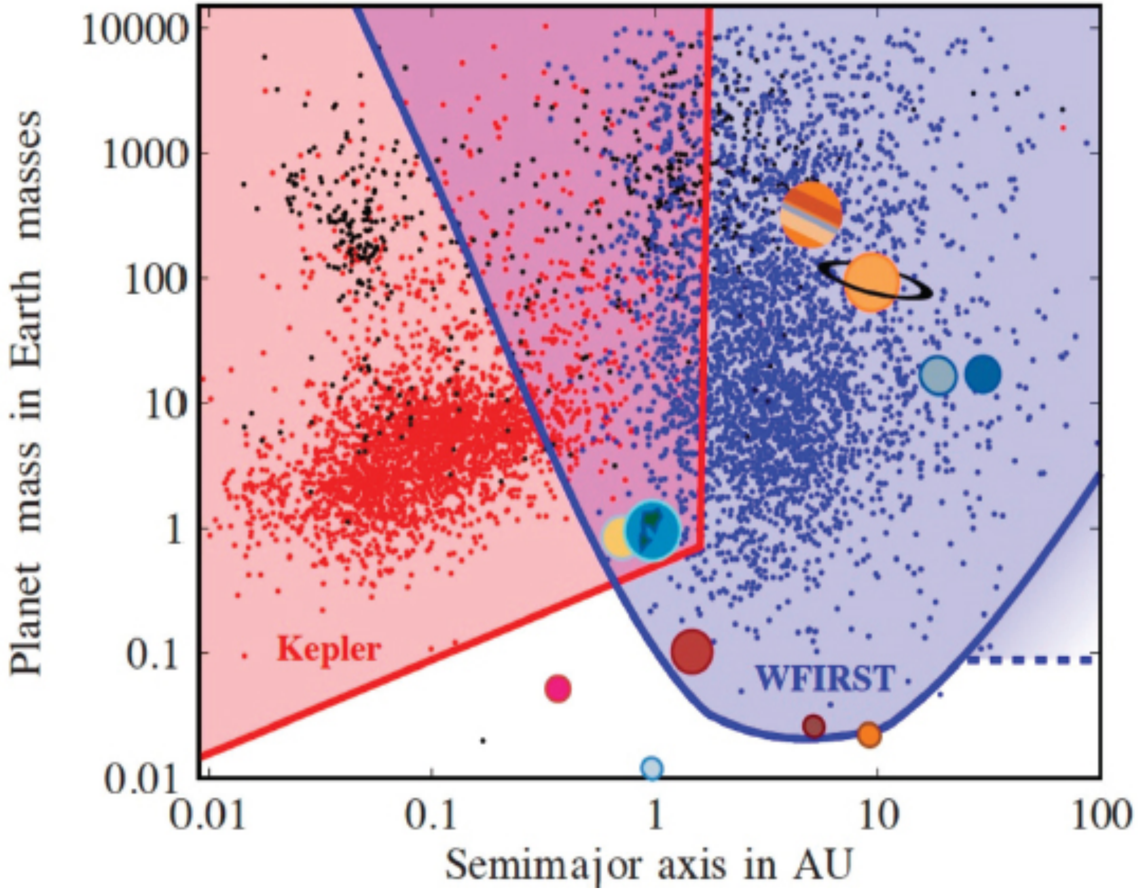
Know Thy Star, Know Thy Planet

October 12, 2017

Importance of Mass Measurements from Microlensing





Suzuki+ 2016, Suzuki+ 2018 in prep

Photo credits: D. Bennett, M. Penny

Planetary Microlensing Events with Physical Parameters

OGLE-2003-BLG-235 (Bennett+ 2006)
OGLE-2005-BLG-071 (Dong+ 2009, Udalski+ 2006)
OGLE-2005-BLG-169 (Bennett+ 2015, Batista+ 2015, Gould+ 2006)
OGLE-2006-BLG-109 (Gaudi+ 2010)
OGLE-2007-BLG-368 (Sumi+ 2010)
MOA-2007-BLG-192 (Kubas+ 2010, Bennett+ 2008)
MOA-2007-BLG-400 (Dong+ 2009a)
OGLE-2007-BLG-349 (Bennett+ 2016)
MOA-2008-BLG-310 (Bhattacharya+ 2017, Janczak+ 2010)
MOA-2009-BLG-319 (Miyake+ 2011)
MOA-2011-BLG-293 (Batista+ 2014, Yee+ 2012)
OGLE-2012-BLG-006 (Poleski+ 2017)
OGLE-2012-BLG-0950 (Koshimoto+ 2016)
OGLE-2012-BLG-563 (Fukui+ 2015)
OGLE-2012-BLG-0026 (Beaulieu+ 2016)
MOA-2013-BLG-220 (Yee+ 2014)
OGLE-2013-BLG-605 (Sumi+ 2016)
MOA-2016-BLG-227 (Koshimoto+ 2017b)
OGLE-2016-BLG-1195 (Yossi+ 2017, Bond+ 2017)

- A typical case of microlensing light curve modelling provides with planet-host star mass ratio q and planet – star separation s in Einstein radius. But does NOT provide planet, host star masses and distances in physical values

- If lucky , parallax measurements from ground and SPITZER can provide us mass and distance measurements

- We need high resolution images to get mass measurements

Mass Measurements with Follow-Up High Resolution Images

- Mass Measurement using isochrones – C.Henderson Talk

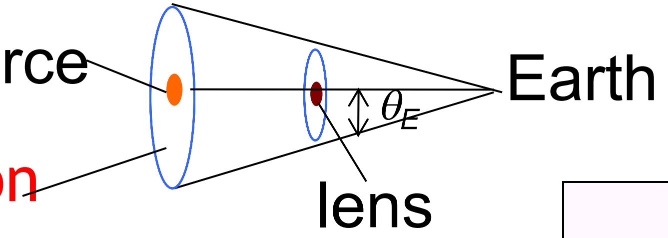
- Mass measurement with lens detection using PSF fitting

We need from light curve fitting:

- Angular Einstein radius (θ_E)
- Planet-host star mass ratio (q)
- Planet- star separation in Einstein radius units (s)
- Lens-source relative proper motion (μ_{rel})

Finite Source Effects & Lens Brightness Measurement Yield Lens System Mass

- Finite source effect
  or lens-source proper motion



Angular Einstein radius $\theta_E = \theta_* t_E / t_*$

θ_* = source star angular radius

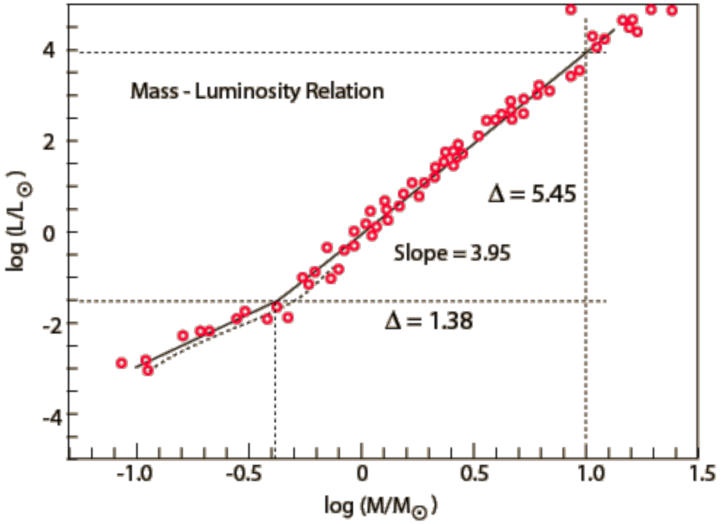
D_L and D_S are the lens and source distances

$$M_L = \frac{c^2}{4G} \theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

- **Lens brightness & color(AO,HST) used in**

  Mass- Luminosity relation

  mass-distance relation ➔ D_L , M_L



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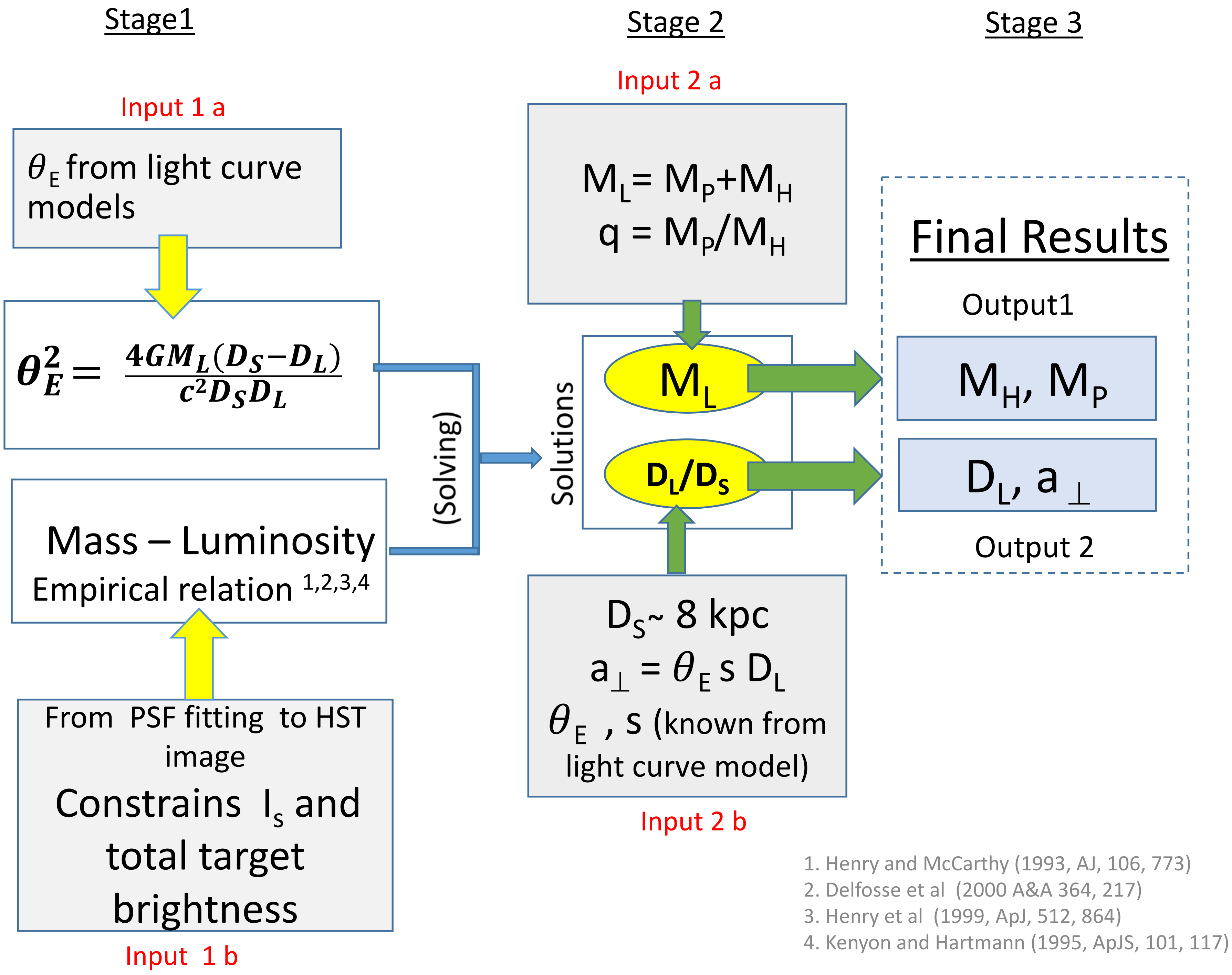
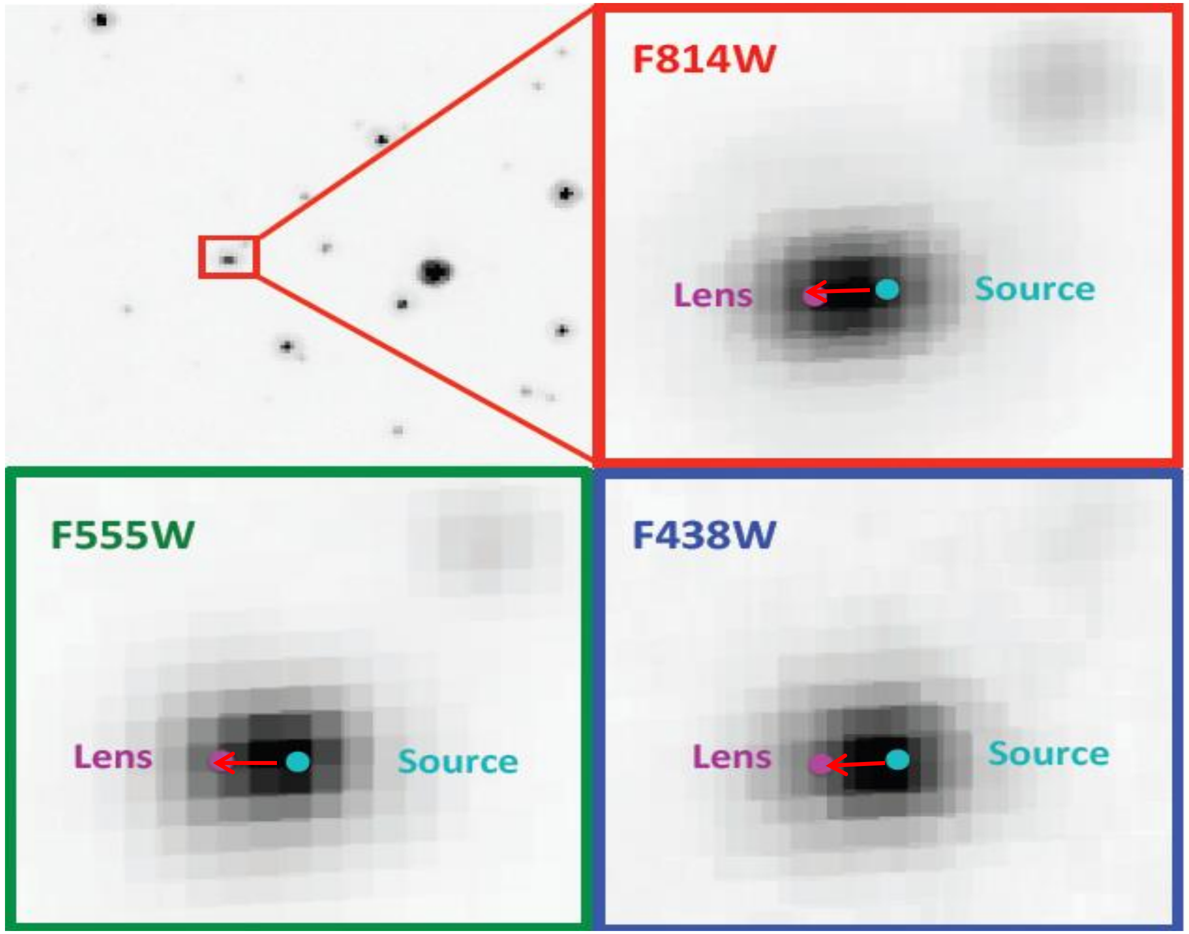

Stage1
Stage 2
Stage 3
Input 1 a
θE from light curve models
θE² = 4GML(DS−DL) / c²DSDL
Mass – Luminosity
Empirical relation 1,2,3,4
From PSF fitting to HST image
Constrains Is and total target brightness
Input 1 b
(Solving)
Input 2 a
ML= MP+MH
q = MP/MH
Solutions
ML
DL/DS
DS~ 8 kpc
a⊥ = θE s DL
θE , s (known from light curve model)
Input 2 b
Final Results
Output1
MH, MP
DL, a ⊥
Output 2
1. Henry and McCarthy (1993, AJ, 106, 773)
2. Delfosse et al (2000 A&A 364, 217)
3. Henry et al (1999, ApJ, 512, 864)
4. Kenyon and Hartmann (1995, ApJS, 101, 117)

HST Observations & PSF Fitting

μ_{rel_l} = 7.39 ± .20 mas/yr

μ_{rel_b} = 1.33 ± .23 mas/yr



Follow –Up Observations of OGLE-2005-BLG-169 taken 6.5 years after the peak

First Direct Relative (Lens-Source) Proper motion of Planetary Microlens Host Star Measured

Bennett, Bhattacharya, Anderson+ 2015

HST Observations & PSF Fitting

μ_{rel_l} =
7.39 ± .20
mas/yr

μ_{rel_b} =
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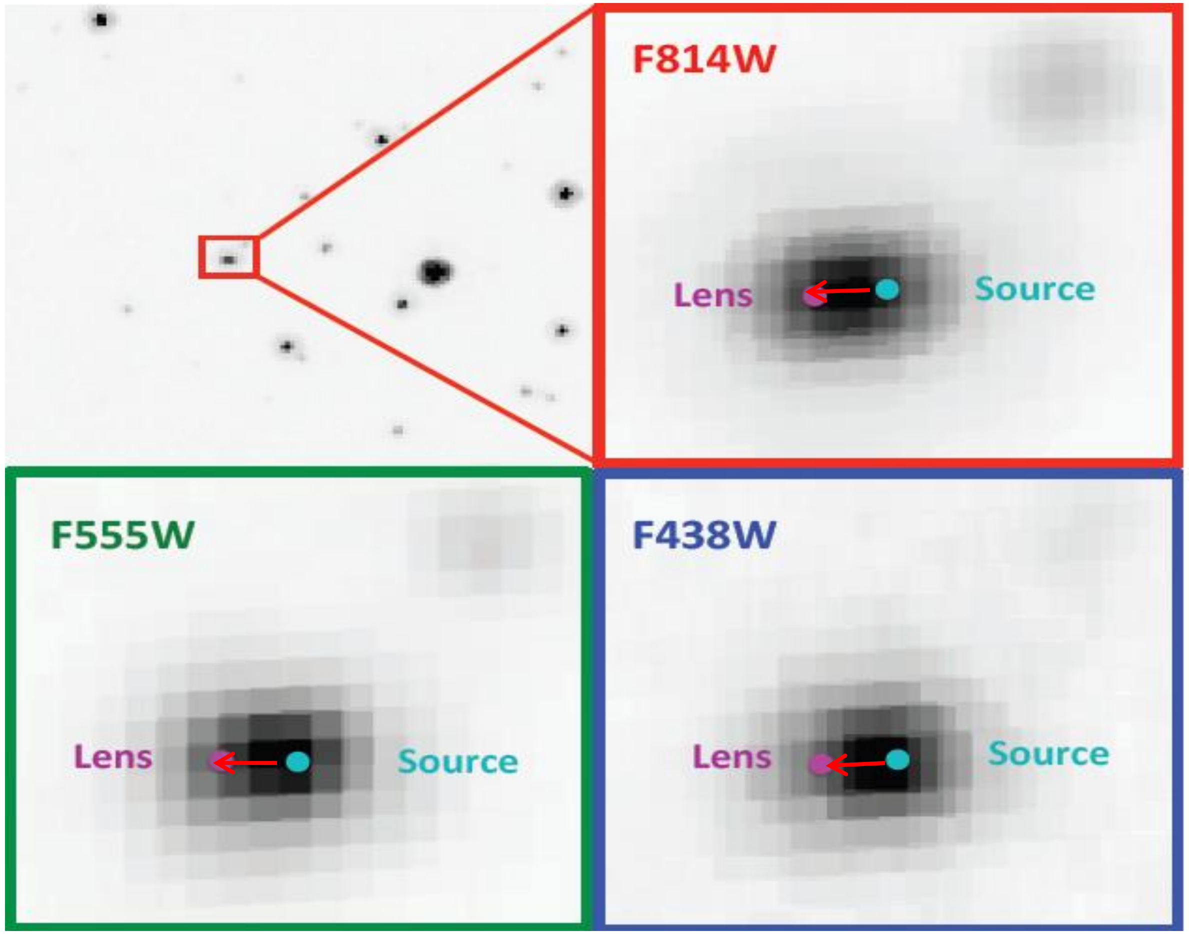
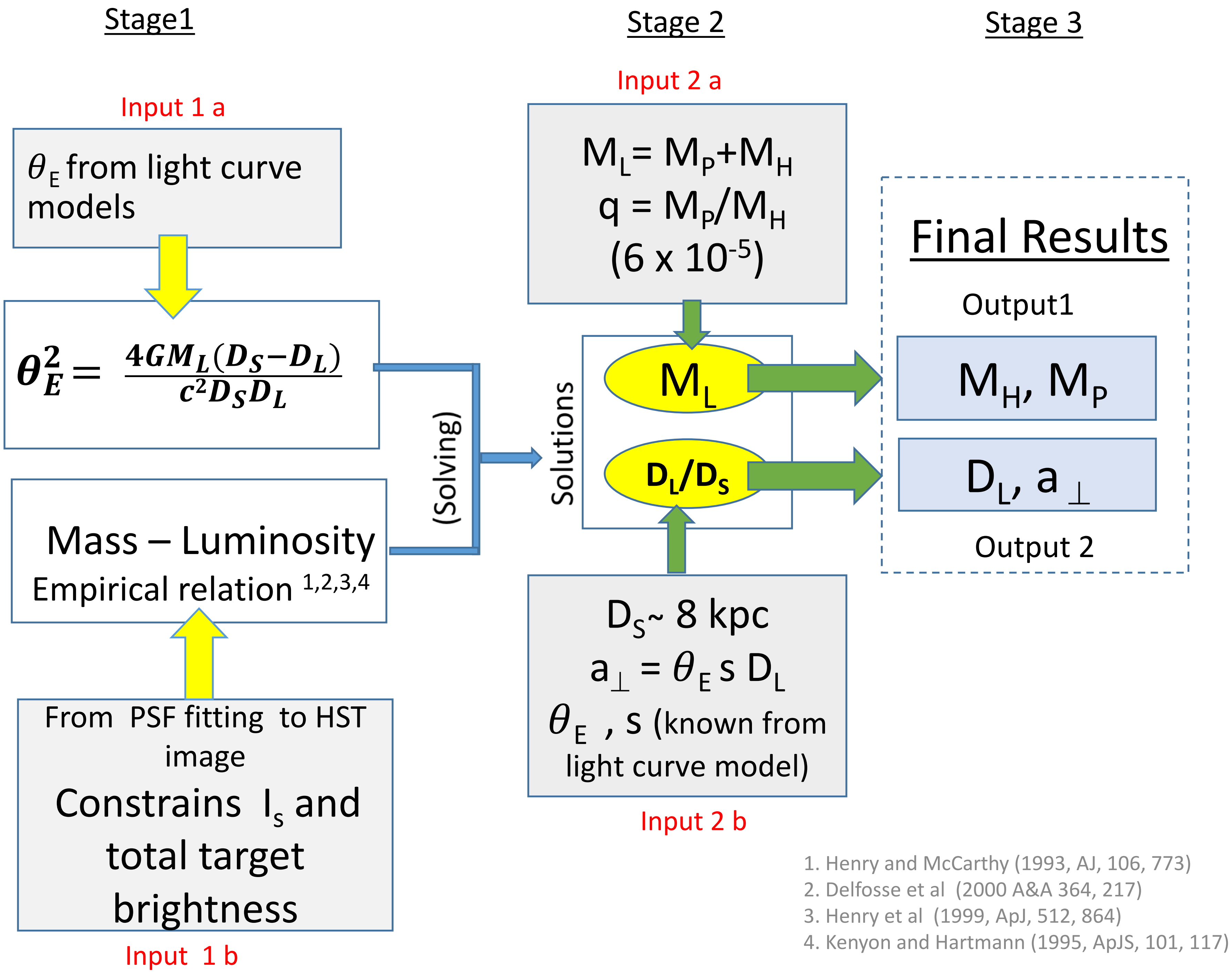
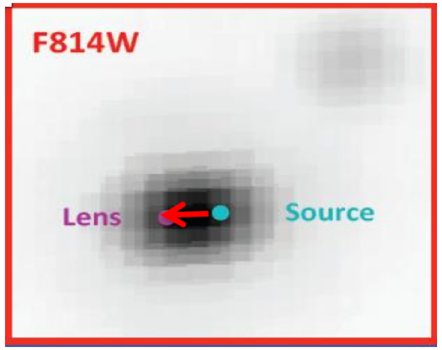


Lens Source brightness similar in I band indicating Lens redder than source hence Lens is also fainter in V and B band

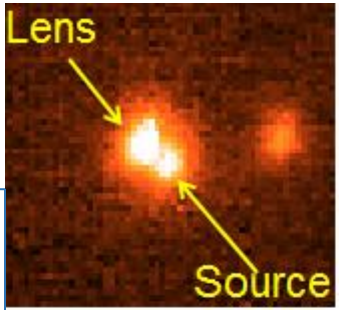
First Direct Relative (Lens-Source) Proper motion of Planetary Microlens Host Star Measured



Stage1
Stage 2
Stage 3
Input 1 a
θ_E from light curve models
$$\theta_E^2 = \frac{4GM_L(D_S - D_L)}{c^2 D_S D_L}$$
(Solving)
Mass – Luminosity
Empirical relation [1,2,3,4]
From PSF fitting to HST image
Constrains I_s and total target brightness
Input 1 b
Input 2 a
$M_L = M_P + M_H$
$q = M_P/M_H$
(6×10^{-5})
Solutions
M_L
D_L/D_S
$D_S \sim 8$ kpc
$a_\perp = \theta_E \, s \, D_L$
θ_E , s (known from light curve model)
Input 2 b
Final Results
Output1
M_H, M_P
D_L, $a_\perp$
Output 2
1. Henry and McCarthy (1993, AJ, 106, 773)
2. Delfosse et al (2000 A&A 364, 217)
3. Henry et al (1999, ApJ, 512, 864)
4. Kenyon and Hartmann (1995, ApJS, 101, 117)



OGLE-2005-BLG-169: HST & Keck



8.3 years after discovery[1]

HST		**Keck**	
μ_{rel_l}	= 7.39 ± .20 mas/yr	μ_{rel_l}	= 7.28 ± .12 mas/yr
μ_{rel_b}	= 1.33 ± .23 mas/yr	μ_{rel_b}	= 1.54 ± .12 mas/yr

Both supports $\alpha \sim 90^\circ$ and $q = 6\times10^{-5}$ model

HST

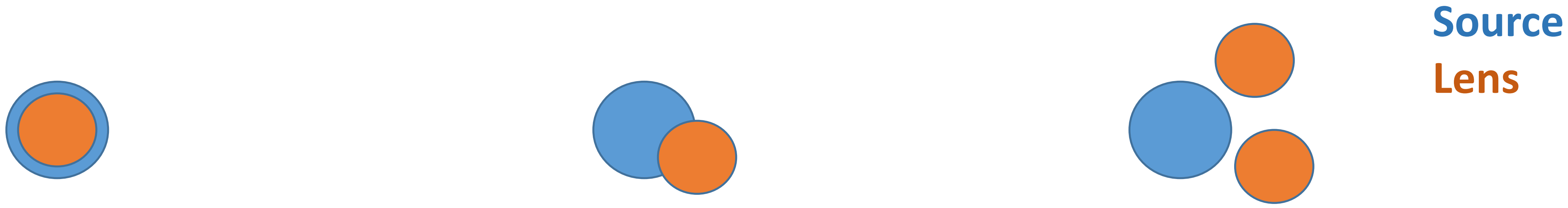
- Host mass: 0.687 ± .021 $M_\odot$
- Planet Mass:
  14.1 ± 0.9 $M_\oplus$
- D_L = 4.1 ± 0.4 kpc
- Projected Separation($a_\perp$):
  3.5 ± 0.3 AU

Keck

- Host mass: 0.667 ± .049$M_\odot$
- Planet Mass:
  13 ± 1.5 $M_\oplus$
- D_L = 3.9 ± 0.4 kpc
- Projected Separation($a_\perp$):
  3.4 ± 0.3 AU

1. Batista et al 2015 , 2. Bennett et al 2015

Ideal condition of Follow up Observations for Mass Measurement



Cannot confirm the lens– too early

Best Condition

Which one is lens ?
Lens or ambient star?
too late

GAIA cannot do this because: PSF fitting

We absolutely need **high resolution follow up** for the current ground based planetary microlensing

In future with WFIRST Space Based Microlensing Survey we will be able to measure mass directly from the survey with lens detection

Planetary Microlensing Events with Excess Flux Detection in High Resolution Images

MOA-2008-BLG-310 (Janczak+ 2010, Bhattacharya+ 2017)
MOA-2011-BLG-293 (Batista+ 2014, Yee+ 2012)
OGLE-2012-BLG-0950(Koshimoto+ 2016)
OGLE-2012-BLG-563 (Fukui+ 2015)
OGLE-2007-BLG-368 (Sumi+ 2010)
MOA-2007-BLG-192 (Kubas+ 2010, Bennett+ 2008)
OGLE-2005-BLG-169 (Bennett+ 2015, Batista+ 2015, Gould+ 2006)
OGLE-2007-BLG-349 (Bennett+ 2016)
OGLE-2012-BLG-0026 (Beaulieu+ 2016)
OGLE-2006-BLG-109 (Gaudi+ 2010)
OGLE-2003-BLG-235 (Bennett+ 2006)
OGLE-2005-BLG-071 (Dong+ 2009, Udalski+ 2006)

MOA-2008-BLG-310

- From Discovery paper[1]:

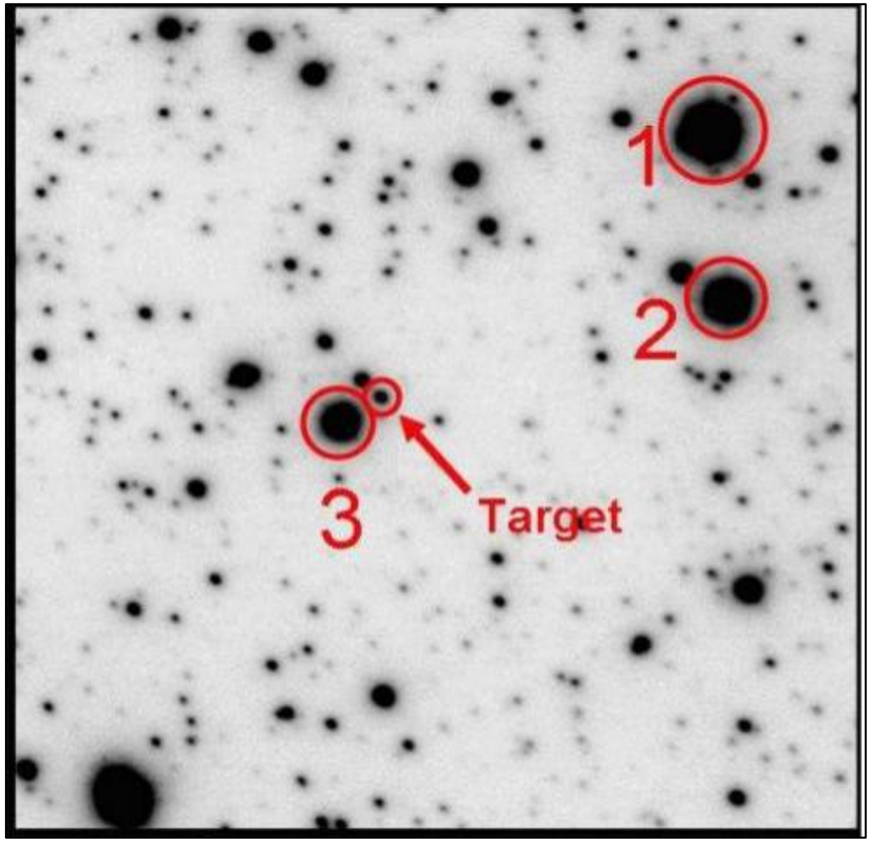
  $q = (3.3 \pm 0.3) \times 10^{-4}$

  Sub Saturn mass planet

  $\mu_{relG} = 5.1 \pm 0.3$ mas/yr

- Excess flux in H band (NACO Data)

- Extra Flux detected on top of source in HST *I* and *V* band data in both epochs 3.6 and 5.6 years later



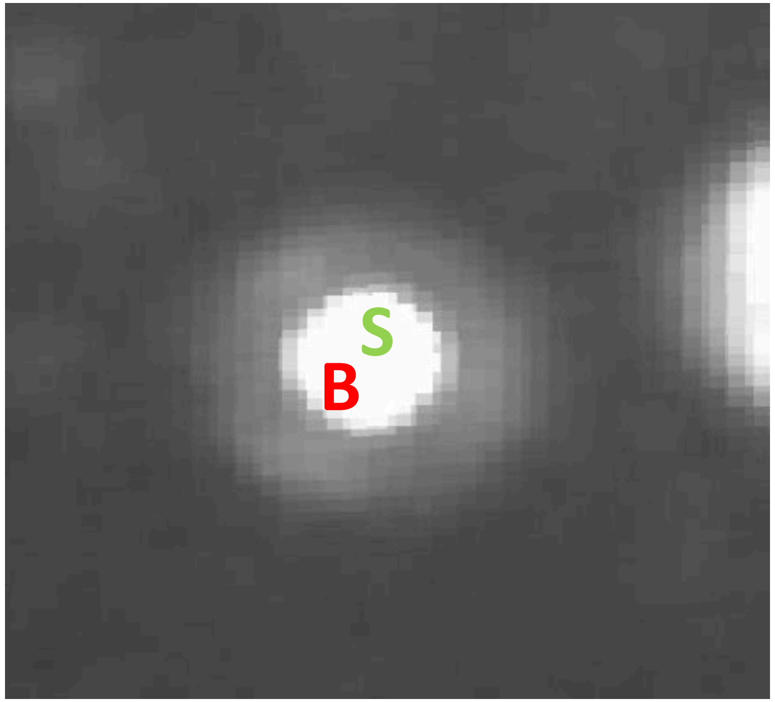
1. J. Janczak et al 2010 ApJ 711 731

MOA-2008-BLG-310

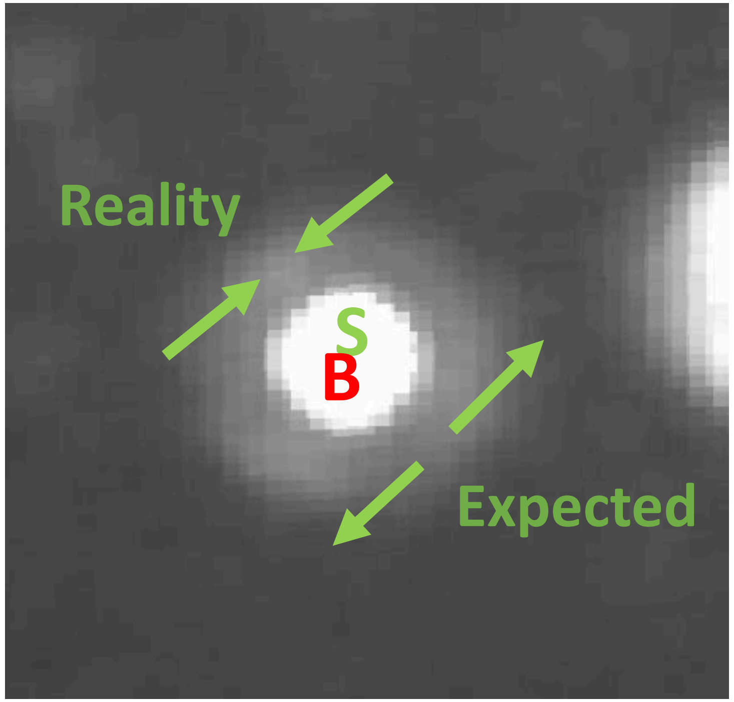
Two star fit – Source Flux Constrained

Source
Blend Star

2012 HST F814W



2014 HST F555W



Source Flux constrained from light curve fitting

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MOA-2008-BLG-310

Two star fit – Source Flux and Lens- Source Separation Constrained

Dual Star Fit	Year	Filter	Magnitude* Star 1	Magnitude* Star 2	Separation (mas)	Separation star 2 - star 1 Δx	Separation star 2 - star 1 Δy	χ^2
Best Fit	2012	I	19.84(0.15)	20.31(0.24)	14.1(3.2)	9.5(2.6)	10.1(2.6)	194.3
		V	21.37(0.18)	21.74(0.56)	15.2(2.9)	6.7(2.5)	13.1(2.1)	193.1
	2014	I	19.86(0.14)	20.28(0.18)	12.2 (3.3)	10.6(1.8)	4.7(2.8)	201.1
		V	21.47(0.22)	21.64(0.27)	11.6(3.7)	10.3(2.2)	6.2(3.1)	195.9
Source Flux Constrained	2012	I	19.47(0.05)	21.35(0.29)	16.6(2.1)	11.2(1.2)	12.4(1.6)	204.2
		V	21.11(0.12)	22.26(0.38)	16.1(2.9)	9.2(2.1)	11.6(2.1)	199.2
	2014	I	19.45(0.05)	21.43(0.31)	14.1(2.1)	12.4(1.2)	6.1(1.2)	210.9
		V	21.11(0.11)	22.31(0.43)	13.5(2.4)	11.6(1.2)	7.6(2.1)	200.9
Source Flux and Separation Constrained	2012	I	19.46(0.04)	21.41(0.21)	17.4(3.4)	11.4(2.5)	12.7(2.3)	214.5
		V	21.09(0.13)	22.28(0.28)	17.3(3.6)	6.5(2.8)	13.6(2.2)	206.2
	2014	I	19.38(0.06)	22.18(0.27)	26.9(7.7)	20.3(7.1)	14.5(3.1)	233.9
		V	21.02(0.09)	22.66(0.48)	26.8(9.3)	23.8(8.3)	12.5(4.2)	218.7

This Table presents magnitudes calibrated to the OGLE-III scale.

χ^2 is high

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MOA-2008-BLG-310

Two star fit – Conclusions

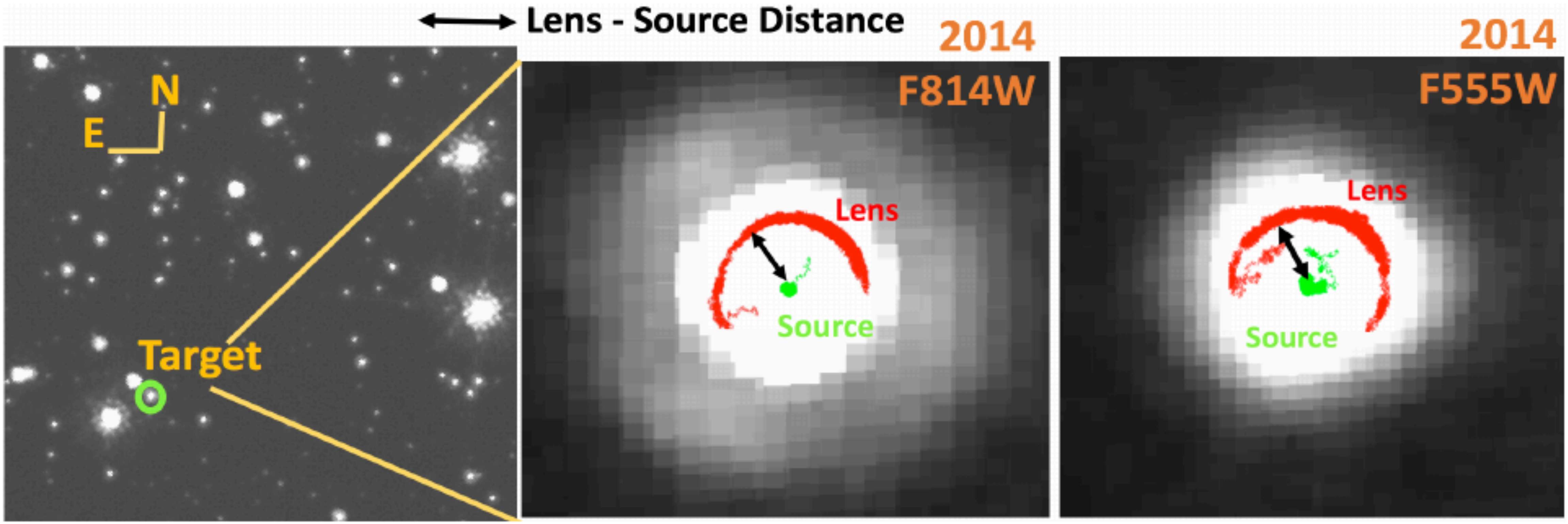
- The Extra flux on top of the source is primarily NOT due to the lens
- Source Companion – The velocity of the blend star is too high to be source companion
- Lens Companion – Velocity measurement is not similar to lens– not a lens companion
- Ambient Star – Possibly , the proper motion is consistent with bulge stars

MOA-2008-BLG-310

Two star fit – Conclusion

The Excess Flux is not necessarily due to the lens primarily.
It is important to verify the lens with the lens-source relative proper motion.

Three star fit – Upper Limit on Lens Mass



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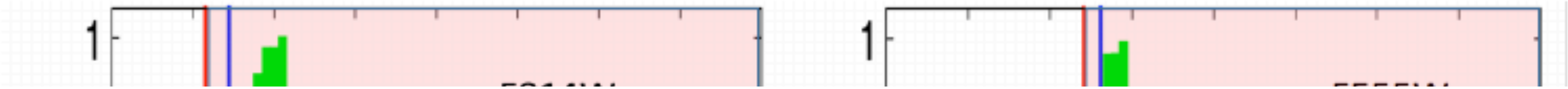
MOA-2008-BLG-310

Three star fit – Upper Limit on Lens Mass



parameter	units	99% confidence		95% confidence	
		I	V	I	V
Host star mass, M_*	$M_\odot$	0.64	0.73	0.61	0.72
Planet mass, m_P	$M_\oplus$	72	82	69	81
Host star - Planet 2D separation, $a_\perp$	AU	1.1	1.1	1.1	1.1
Lens distance, D_L	kpc	7.8	7.8	7.8	7.8

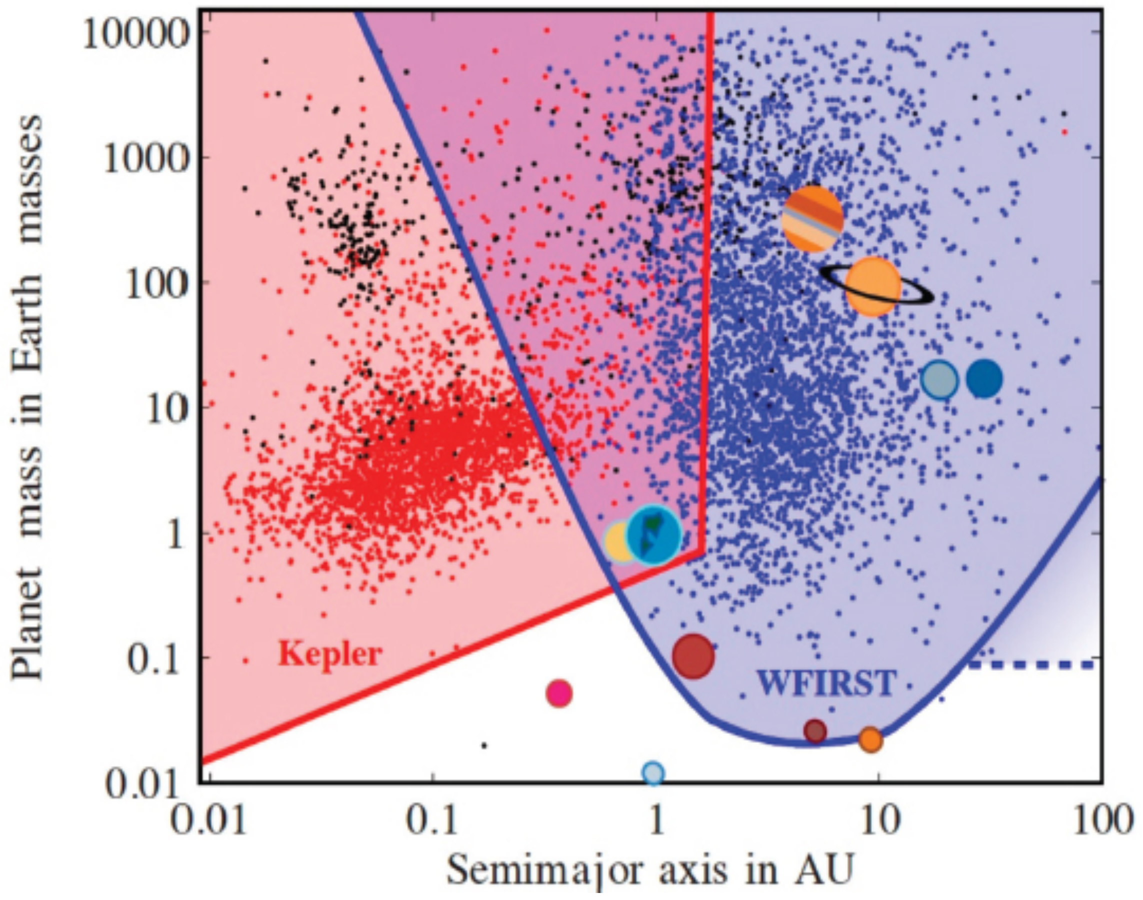
$I = 22.15, V = 23.41$ (99% confidence)

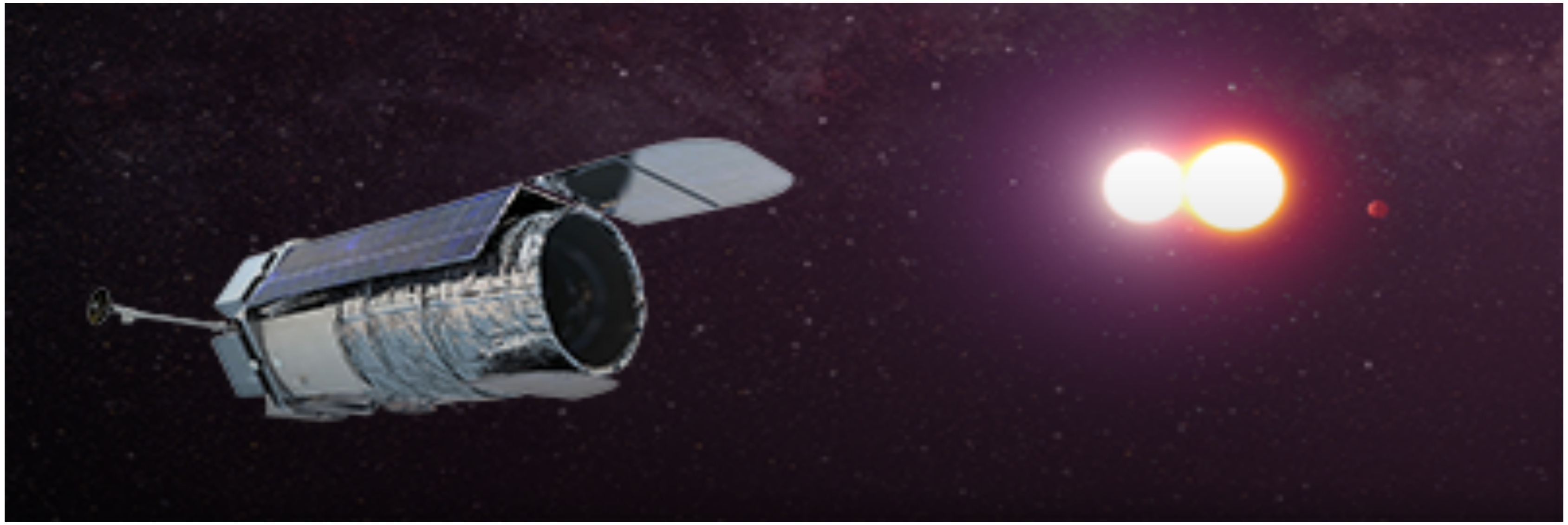
$I = 22.44, V = 23.62$ (95% confidence)

Bhattacharya+ 2017

Conclusions

- Space based microlensing survey like WFIRST will be able to not only detect the microlensing exoplanets but will also measure the mass of the exoplanets directly from the survey.
- Extra Flux detection on top of the source is not necessarily the lens. We have to be careful to verify the lens with relative proper motion in high resolution images.
- We can still get an upper limit on the mass measurements.





Thank You